

# Lunar gamma ray emission seen during the first year by Fermi

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We report the detection of the lunar gamma-ray emission during the first year of Fermi-LAT observations. Such emission is produced by cosmic ray nuclei interacting with the lunar surface. Thanks to the solar minimum conditions and the reduced effects of heliospheric modulation, the lunar flux was at its maximum due to the increased flux of Galactic cosmic rays hitting the lunar surface. Fermi-LAT instrument has a superior sensitivity, angular resolution, and observes the whole sky every two orbits. It is the only gamma-ray mission capable of detecting the lunar emission with high confidence and to monitor it over the full 24th solar cycle. We also report the status of a search of the gamma-ray emission from major planets and asteroid populations in the ecliptic plane.

## I. INTRODUCTION

The  $\gamma$ -ray emission produced by solid solar system bodies is due to the interactions of Galactic cosmic ray nuclei (mainly protons) with their surface layers. The main processes involved are the production and decay of  $\pi^0$ s and kaons by ions, bremsstrahlung by electrons and Compton scattering of the secondary photons. The  $\gamma$ -ray telescope EGRET on the *Compton Gamma-Ray Observatory* (CGRO), operated from 1991 to 2000 and detected the  $\gamma$ -ray emission from the Earth [1], the Moon [2, 3], and the Sun [2]. Nuclear  $\gamma$ -ray emission produced in the lunar surface in low-energy cosmic ray and secondary neutron reactions was observed by the Lunar Prospector [4] and used in the analysis of the composition of the regolith. Although similar physical processes are involved, the  $\gamma$ -ray spectra of the Earth, the Moon, and the Sun are very different. The Moon is so far the only observed  $\gamma$ -ray emitting body with the solid surface. For the Sun, the  $\gamma$ -ray emission from the disk, due to the interactions of cosmic ray nuclei with the solar atmosphere [2, 5], is accompanied by extended and brighter  $\gamma$ -ray emission due to the inverse Compton scattering of Galactic cosmic ray electrons off solar photons [2, 6, 7].

Early analysis of EGRET observations of the Moon yielded the integral flux of  $F(E > 100 \text{ MeV}) = (4.7 \pm 0.7 \text{ syst}) \times 10^{-7} \text{ cm}^{-2} \text{ s}^{-1}$  [3]. A later re-analysis confirmed the detection and yielded a flux  $F(E > 100 \text{ MeV}) = (5.55 \pm 0.65) \times 10^{-7} \text{ cm}^{-2} \text{ s}^{-1}$  averaged over the entire mission duration [2].

Calculations of interactions of cosmic rays with the lunar surface are fairly straightforward and involve a well-measured spectrum and composition of cosmic rays near the Earth and composition of the Moon rock, the regolith, which was quite rigorously studied using the samples returned by the lunar missions as well as by the remote sensing. The first calculation of the lunar  $\gamma$ -ray emission was done by Morris[8] using the cross section data and techniques available at that time. Recent detailed flux calculations[9] depends on the level of heliospheric modulation and is generally consistent with observations and were done using the Geant4 framework[10]. It was shown that

the spectrum of  $\gamma$ -rays from the Moon is steep with an effective cutoff around 3–4 GeV (600 MeV for the inner part of the lunar disk). Due to the kinematics of the collision, the secondary particle cascade from cosmic ray particles hitting the lunar surface at small zenith angles develops deep into the rock making it difficult for  $\gamma$ -rays to get out. Therefore the lunar  $\gamma$ -ray emission is produced by a small fraction of splash particles in the surface layer of the moon rock. High energy  $\gamma$ -rays can be produced by cosmic ray particles hitting the Moon surface with a more tangential trajectory; thus only a very thin limb contributes to the high energy emission.

A similar emission should be detected from any other solid object in the solar system. Therefore planets should emit  $\gamma$ -rays produced from pion-decays coming from the hadronic interactions by cosmic-rays hitting the surface or the atmosphere of these bodies. Recent papers[11, 12] have studied interactions of cosmic rays with populations of small bodies in the solar system. In particular, gamma-ray emission from asteroids, rocks, and dust at the outskirts of the solar system, e.g., the Oort Cloud[15], may contribute to the isotropic gamma-ray background. The gamma-ray emission from the Moon[9, 13] can serve as a template for such studies.

We report here the updated observations of the lunar  $\gamma$ -ray emission, previously presented[16, 17, 18], and the status of a search for emission from smallest solid objects, such as Jovian trojans[19].

## II. DATA SELECTION

The data used in this study were collected during the first year beginning from 4 August 2008 during the solar minimum of activity. We have applied a zenith cut of  $105^\circ$  to eliminate photons from the Earth's limb, and used the "Diffuse" class [20], corresponding to events with the highest probability of being true photons. The analysis is performed using the standard maximum-likelihood spectral estimator provided by the LAT Science Tools[25] package (version v9r15), which is available from and using p6\_v3 post-

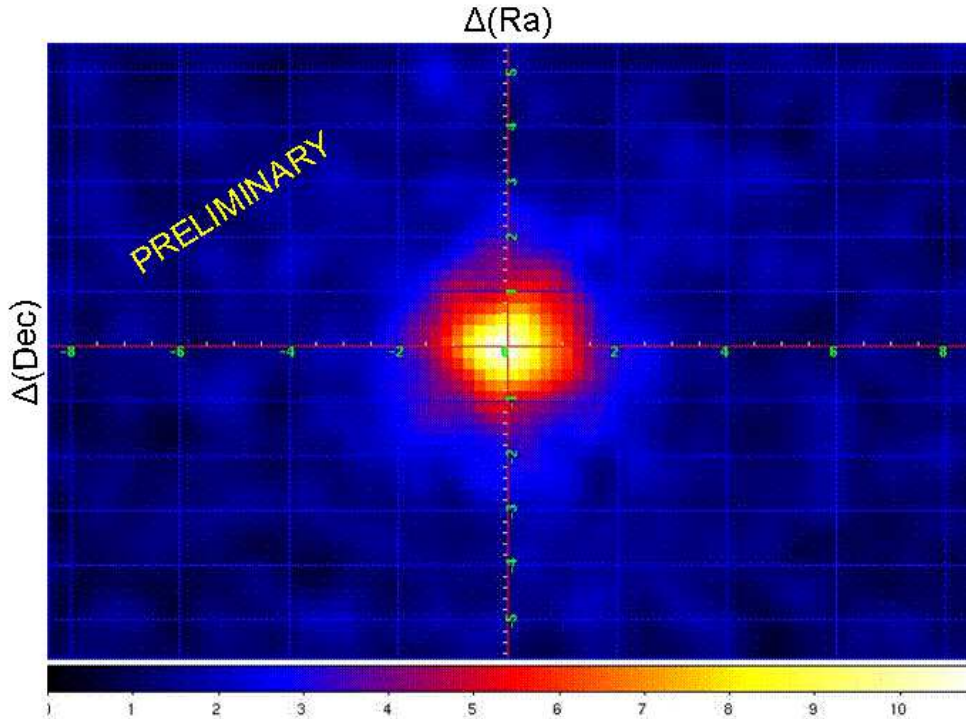


FIG. 1: Count map in a Moon centered frame, Right Ascension and Declination offsets in degrees respect to the Moon position in abscissa and ordinate respectively. The offset ranges are  $\pm 8^\circ$  for Right Ascension and  $\pm 5^\circ$  for Declination. The image has been obtained by using photons with  $E > 100$  MeV, a bin width of 0.2 degrees with a gaussian smoothing 2 bin radius. The colour scale is linear with the counts.

launch Instrumental Response Functions (IRFs). We also used the standard Science Tools provided by the Fermi Science Support Center, version v9r15 and IRFs (Instrumental Response Functions) version P6\_V3.

The position of the Moon has been computed using a JPL[24] library interface. Photon events for analysis were selected in a frame, 15 degree radius, and centered on the instantaneous lunar position. We used the unbinned likelihood analysis technique typically used for astrophysical sources but, since the Moon moves quickly across the sky, we had to take additional precautions to determine the emission spectrum. In order to avoid strong variations of background photons, we excluded time intervals when the Moon was close to the galactic plane or bright sources. We therefore required that the Moon was at least  $30^\circ$  from the galactic plane i.e.  $|B_{moon}| > 30^\circ$ , and we remove also any time intervals in which any individual bright object has an angular distance less than  $5^\circ$  from the Moon. The real difficulty in obtaining a consistent lunar  $\gamma$ -ray flux is the variation of the diffuse galactic background and extragalactic emission as the Moon moves through the sky. Therefore to evaluate the diffuse background in proper way we use the fake source method[22, 23] by defining a "fake" moon that followed the lunar trajectory but 30 degrees displaced along the true trajectory. The "fake" Moon was therefore exposed to the same celestial sources as the true

Moon and the event observed in the frame centered on the fake Moon make a good description of the diffuse background. Moreover we verify that this background estimation is consistent with the background flux values measured using larger values of angular displacement along the lunar trajectory to define the fake source.

### III. LUNAR OBSERVATION RESULTS

Fig. 1 shows the count map of photon events with  $E > 100$  MeV in offsets of celestial coordinates relative to the Lunar position. Emission from the Moon is clearly visible and centered on the expected location in this relative coordinate frame.

Fig. 2 shows the count map of the events with  $E > 100$  MeV and within a  $15^\circ$  from the Moon center projected onto Right Ascension while in Fig.3 the events are projected onto Declination. The coordinates are offsets in degrees of celestial coordinates relative to the Moon position. In these figures the counts observed for the "fake" Moon are superimposed and demonstrate the need to carefully consider the background before any lunar analysis can be performed. Simulated data confirm that the observed shape is in agreement with a pointlike source and the calcu-

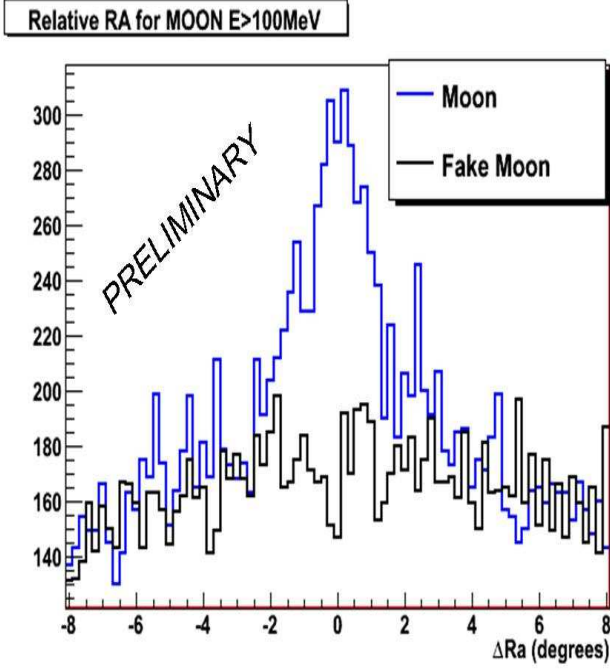


FIG. 2: Count map of photons having an angular distance less than  $15^\circ$  from the Moon center and with  $E > 100$  MeV, as a function of Right Ascension offsets in degrees respect to the lunar nominal position. Superimposed as dashed line the fake Moon count map distribution. Observed data are consistent with the expected angular resolution for 100 MeV photons.

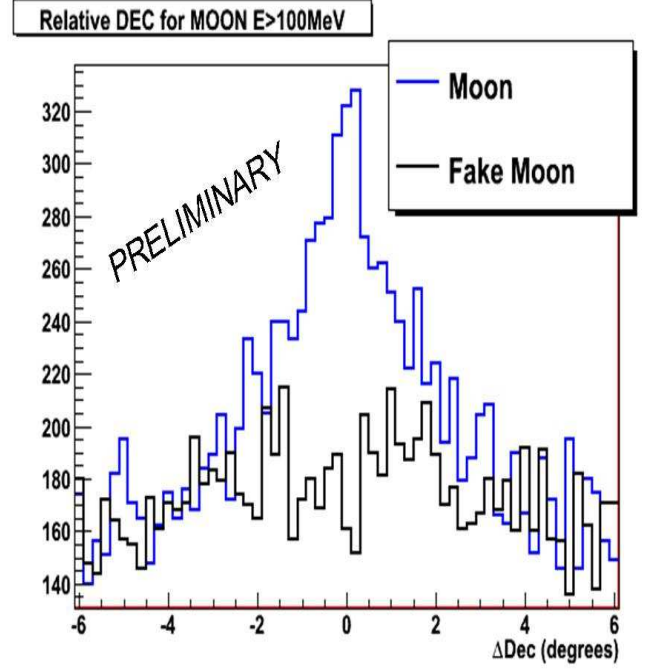


FIG. 3: Count map of photons having an angular distance less than  $15^\circ$  from the Moon center and with  $E > 100$  MeV, as a function of Declination offsets in degrees respect to the lunar nominal position. Superimposed as dashed line the fake Moon count map distribution. Observed data are consistent with the expected angular resolution for 100 MeV photons.

lated point spread functions[26] of the LAT[20] for the expected lunar gamma-ray spectrum. In a more detailed analysis[21] of a one-year database we will perform carefully the analysis of the shape of emission to determine its true extent and whether we can discern evidence for the expected limb brightening.

To study the spectrum of the gamma-ray emission we have used the standard unbinned maximum-likelihood spectral estimator provided with the LAT science tools `gtlike`. This preliminary analysis was performed by fitting the "fake" moon data to model the background and the Moon data sample with either a simple power law or other functional forms like a log-parabola summed to the background model.

The fitted values obtained using a simple power law give a good test-statistics value of 7320.3 (defined as  $TS = 2(\log L - \log L_0)$ , being  $L$  and  $L_0$  the likelihood values when the source is considered or not) and indicate a power law index of  $-3.13 \pm 0.03$ . As a result of these fits we estimate the observed flux as  $F(E > 100 \text{ MeV}) = 1.1 \pm 0.2 \times 10^{-6} \text{ cm}^{-2} \text{ s}^{-1}$ . The error includes the estimation of overall systematic error of about 20% for these measurements, due essentially to the uncertainties of the detector effective area and due to the inefficiencies in gamma-ray detection due to pile-up effects from near coincidences with cos-

mic rays in the LAT detector. A comparison of our data with models[9] are in good agreement with the shape of the expected spectrum and compatible with the levels computed of solar activity. The detailed analysis of the differential spectrum of the lunar emission, in particular below 100 MeV[9, 13], is currently in progress.

Our measurement of the lunar  $\gamma$ -ray flux is about twice the average flux measured  $5.5 \times 10^{-7} \text{ cm}^{-2} \text{ s}^{-1}$  previously obtained by EGRET[3]. However we know that the EGRET data subdivided into two subsamples, data taken during the solar maximum 1991 – 1992 and those taken during period of moderate activity 1993 – 1994, yield to  $3.5 \times 10^{-7} \text{ cm}^{-2} \text{ s}^{-1}$  and  $7 \times 10^{-7} \text{ cm}^{-2} \text{ s}^{-1}$  respectively, demonstrating that the flux is higher near the solar minimum. Therefore the *Fermi*-LAT observations reported in this paper, that are taken entirely during the period of solar minimum, should be better compared with the EGRET subsample taken during the solar low level of activity. The neutron monitor rate[27] during the period of observations by *Fermi* was, at least, 10% higher than the ground neutron rate values reported by EGRET[3] at that time. We conclude therefore that there is a reasonable agreement with previous measurements if the solar activity is taken into account.

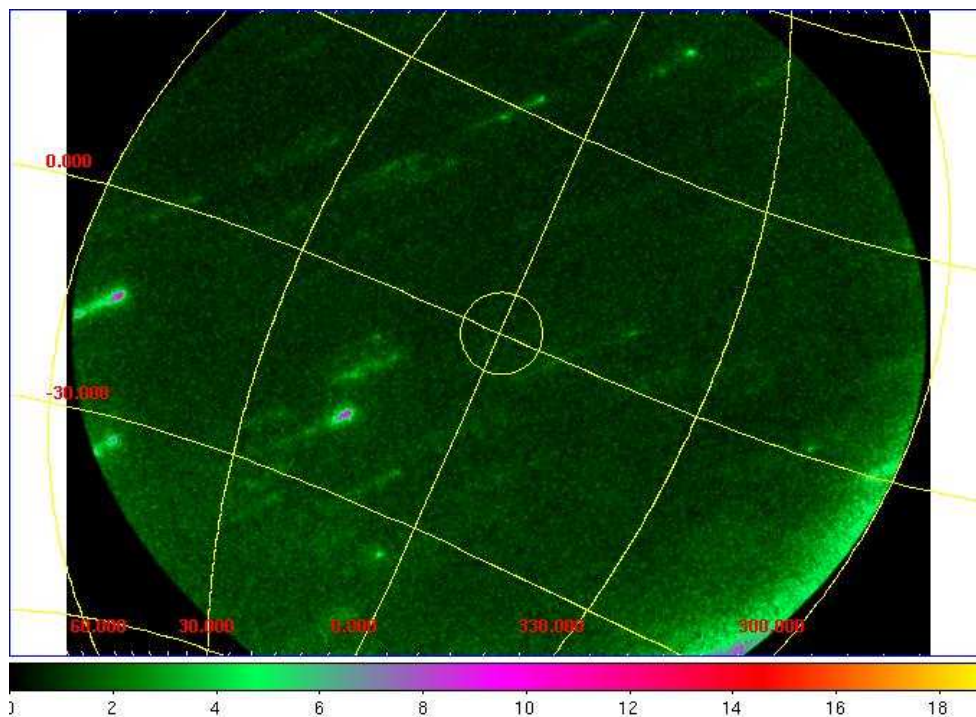


FIG. 4: Photon count map centered on Saturn position (marked with a circle) and collected during the first 10 months starting from august 2008. The colored vertical scale is linear and smoothing has been applied to the image. The bin width used is  $0.2^\circ$ . The coordinates are celestial offset respect of Saturn position, the axes represent ecliptic coordinates.

#### IV. OTHER SOLAR SYSTEM SOURCES

A similar strategy has been used to search for the  $\gamma$ -ray emission from the most interesting solar system objects, starting from the major planets. We have considered the photon count maps in the direction of major planets, including Jupiter and Saturn. For any selected object we have examined the count map to look for any evident excess of counts. No evidence of photon excess from the regions centered on these planets or within several degrees from these sources was found during the first 10 months of observations. Fig. 4 shows the count map of the events in celestial coordinates offsets relative to Saturn position. The search for the emission from populations of small solar system bodies[15] is currently in progress.

#### V. CONCLUSIONS

The gamma-ray emission from the Moon discovered by EGRET has been confirmed by *Fermi* and agrees in intensity for emission models that take into account the level of solar modulation. Our preliminary flux estimation for the lunar  $\gamma$ -ray emission is  $F(E > 100 \text{ MeV}) = 1.1 \pm 0.2 \times 10^{-6} \text{ cm}^{-2} \text{ s}^{-1}$  with a spectral index of  $-3.13 \pm 0.03$  obtained by fitting a simple power law between 100 MeV to 1 GeV. The

lunar flux measured is higher than previous measurements but reasonably in agreement with the cosmic ray flux increase due the solar minimum activity in this solar cycle. We expect that with a larger sample of events available after accumulating data for one year, *Fermi* should be able to explore the other features of the lunar spectrum, e.g. the  $\pi^0$  peak and also to resolve the spatial structure of the emission from the lunar disk. We have started a search for the emission from other bodies of the solar system objects too, in particular from Saturn and Jupiter regions. During the first 10 months we don't have evidence of  $\gamma$ -ray emission in these regions. The search for the emission from populations of small solar system bodies is currently in progress.

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  - [24] see <http://iau-comm4.jpl.nasa.gov/access2ephys.html>
  - [25] **gtlike** is the standard maximum-likelihood spectral estimator included in Science Tools
  - [26] see <http://fermi.gsfc.nasa.gov/ssc/data/analysis/documentation/>
  - [27] see for example tables from <http://neutronm.bartol.udel.edu> or <http://www.ngdc.noaa.gov/stp/SOLAR/ftpcosmicrays.html>